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Study of the ion plasma flow generated by a high-current vacuum arc

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Abstract. The vacuum arc discharge is intensively explored for a long time. It acts as a source of multiply charged plasma. The results of the special type plasma gun (5–10 kA, 12 μs) ion flow study with high temporal resolution and the electrode erosion dependences on the amplitude of the current pulse are presented in the research. The ion flow intensity had good reproducibility from series to series, while the values of total mass erosion differ significantly for different series of experiments under the same conditions. The ion erosion was measured to be significantly higher than that for arc sources with currents up to 1 kA.

1. Introduction

The high current pulsed plasma gun investigated in the present work is a special type of ion source. The common sense about ion sources suggests that it must have stable well repetitive properties. That's why industrial ion sources based on vacuum arc [1] use long high-current discharge pulses. It is revealed [2], that ion flow parameters of ion sources with common scales (usually dozens of cm) become stable after tens of microseconds. Thus, to make a reliable ion source with repetitive stable parameters, it is necessary to use long term (> 100 μs) high-current discharge pulse. Such ion sources are well investigated. The majority of scientific papers are devoted to research and development of ion sources with relatively long current pulses.

Ion sources based on a short vacuum discharge can also be used in industry and scientific research. These sources will have an advantage for short-term processes. In such methods, a long vacuum discharge is not necessary or even harmful. In particular, such processes are used for pulsed neutron sources [3]. Also, a short pulse source is used to create a plasma load for fast (≈ 100–200 ns) z-pinch implosion driven by pulsed power machine [4–7]. In this case, the plasma pinching takes place approximately several microseconds from the beginning of the arc discharge in the ion source. In this process, the source plasma is significantly transient. The temperature, concentration and charge composition of the plasma can vary considerably over time in the region where the plasma column is pinched. This fact can bring complexity when creating an installation with stable parameters. However, if the time dependences of the concentrations, velocities, and mass and charge composition of the plasma in the pinch area are accurately determined, then it is possible to control the installation parameters depending on the delay time of the z-pinch driver current from the start of the ion source discharge. This work is devoted mainly to measuring the temporal and spatial dependence of the ion current of a pulsed microsecond vacuum arc plasma source.

2. Experimental setup and methods

The ion flow produced by pulsed, high-current vacuum arc was studied using small sized ion collectors. Figure 1 provides a schematic view of the electrode arrangement and positions of small size ion collectors. The simplest design of the plasma gun was chosen, which will be useful for creating a “point z-pinch” [5]. A coaxial plasma source with a 1 mm cathode-anode gap was used. The copper cathode had the shape of a cylinder with a diameter of 2 mm and length of 2 mm. The anode was made in the form of a hollow cylinder with an internal diameter of 2 mm and a length of 5.5 mm. Iron and molybdenum were used as anode materials. Polyethylene was chosen as insulator material. All experiments were performed in the vacuum chamber, which was pumped out to pressure about 10^{-4} mm Hg. In this work, a vacuum arc was powered by a pulse generator, which provided current pulse of 12 μs (FWHM) duration and a current amplitude up to 10.8 kA at a charging voltage up to 10 kV (see figure 2). Generally, the experiment consisted of several dozen pulses with a constant amplitude. After each series, the cathode and the insulator were replaced.

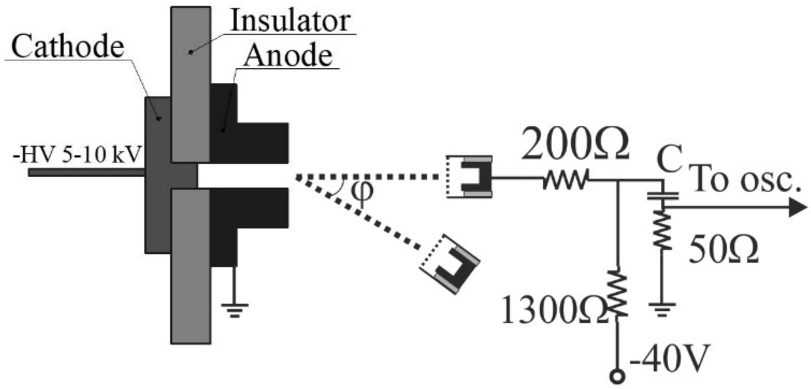

Figure 1. Experimental setup.

Several research methods have been used:

- Mass measurements of the cathode, anode and insulator after experiment series.
- Photography of the arc discharge.
- Analyzing parameters of plasma ion flux using small-sized ion collector analyzers.

The last method allows to reveal the angular and temporal parameters of ion flow. The ion analyzer was a brass cylinder with a diameter of 8 mm and a length of 20 mm. Inside at 8 mm from the entrance, there was a particle collector shaped as a Faraday cup with a diameter of 2 mm and a depth of 1 mm. The entrance aperture was made of copper foil with 9 holes with a diameter of 200 μm. The negative potential of -40 V was applied to the particle collector. The signal of the collector was recorded with a multi-channel oscilloscope after that it was analyzed. Measurements took place at different angles (from 0 to 60°) and distances (from 10 to 25 cm).

In order to obtain the dependence of the total current on time and the overall charge of the ions, it is necessary to integrate the original data over the angles and time through the hemisphere:

$$I(t) = 2\pi \int_0^{\pi/2} R^2 \sin(\varphi) J(t,\varphi) \mathrm{d}\varphi , \tag{1}$$

where $I(t)$ is the dependence of the total current on time; R is the distance from the detector to the source; $J(t, \varphi)$ is the ion current density as a function of time and angle.

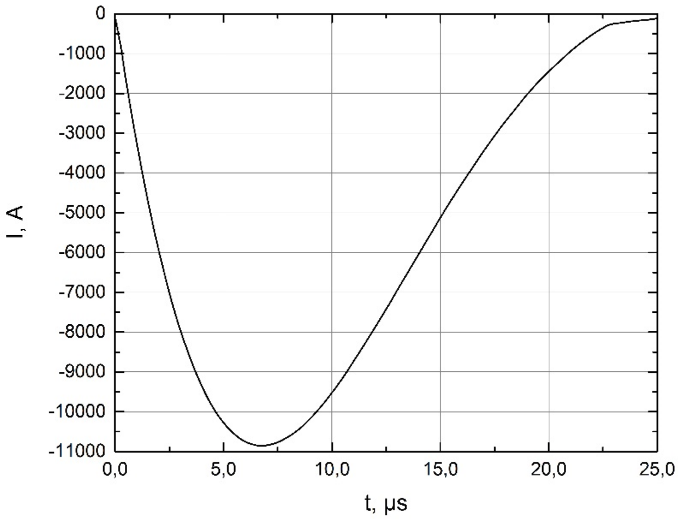

Figure 2. Vacuum arc current pulse at a charging voltage 10 kV.

3. Results

The configuration of electrodes of the ion source was chosen so that the plasma torch had a narrow solid angle. Therefore, an anode with a relatively long and narrow hole was used. As a result, high-pressure plasma was created in the area in front of the cathode and in the anode cavity, which led to melting and splashing of the anode material. A large number of particulates were observed during an arc discharge pulse figure 3. The study of the captured particles showed that they were molten drops of cathode and anode materials. To determine the effect of the anode material on the erosion of the arc discharge, anodes made of iron and refractory molybdenum were used. As a result, data were obtained on the temporal and spatial distribution of the ion current, as well as the total ion erosion for the iron and molybdenum cathodes.

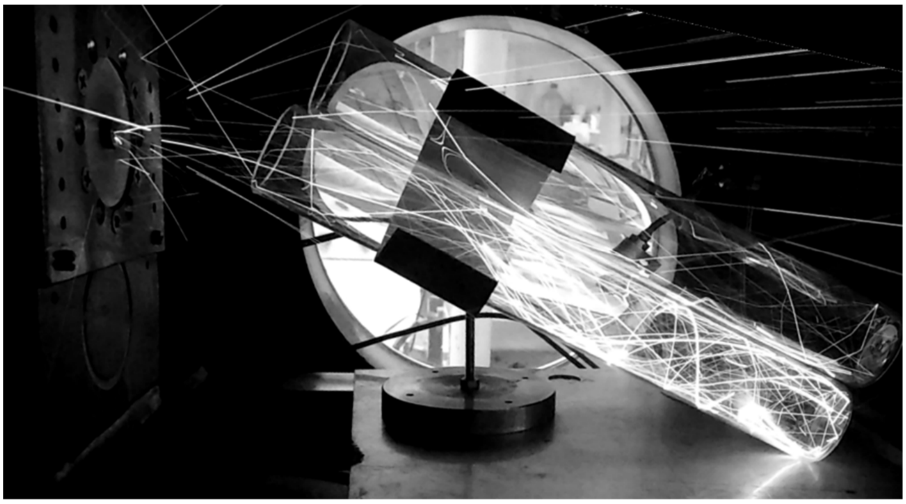

Figure 3. Photo of macroparticle traces after 10 kA discharge.

3.1. Copper cathode – iron anode

The measurement results of the spatial and temporal dependence of the ion current for charging voltages U of 5, 8, 10 kV are presented in figures 4–6.

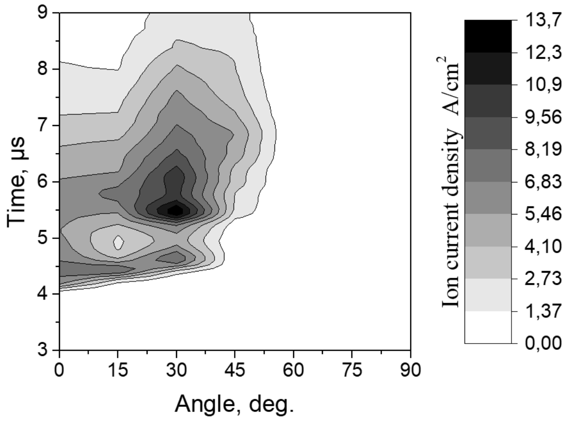

Figure 4. Time and spatial distribution of ion current for $U = 5$ kV. Iron anode.

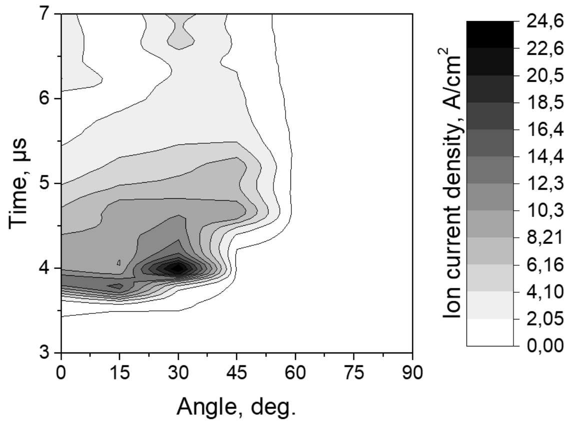

Figure 5. Time and spatial distribution of ion current for $U = 8$ kV. Iron anode.

The measurement results show that the plasma torch had an expansion angle up to 45°. The maximum ion current is at a 30° angle from the axis of the plasma source. At the same time, there is a local minimum on the plasma source axis, which is an unexpected fact. Moreover, for the values of $U = 8$ and 10 kV, the delay of the plasma front arrival on the axis of the plasma source relative to the direction by 15 degrees is also noticeable. The diagrams also show the existence of two plasma fronts: the first front propagates in the angle of 0–15 degrees. The speed of this front is about 3.5×10^6 cm·s^{-1} for $U = 5$ kV and 4.5×10^6 cm·s^{-1} for $U = 10$ kV. The second front extends to 20–40 degrees angles. The speed of the second front is 2.7×10^6 cm·s^{-1} for $U = 5$ kV and 4×10^6 cm·s^{-1} for $U = 10$ kV.

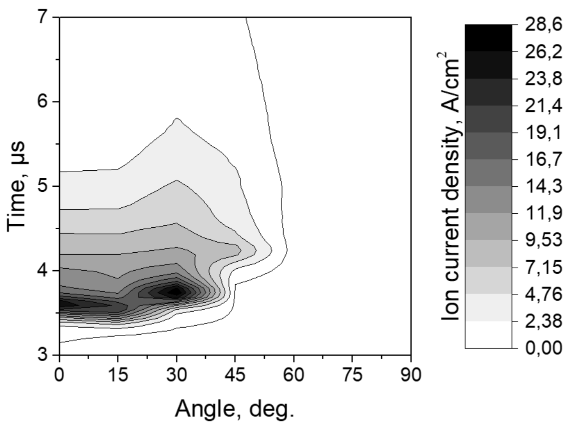

Figure 6. Time and spatial distribution of ion current for $U = 10$ kV. Iron anode.

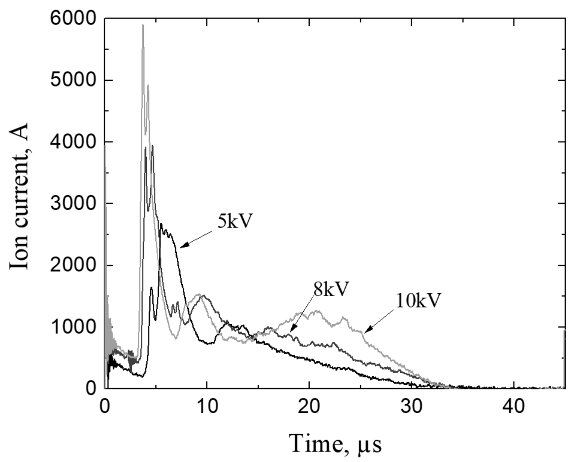

Figure 7. Calculated total ion current at hemisphere with 15 cm radius. The moment of time "0" corresponds to the onset of the arc current pulse.

The ion current integrated over the surface of a unit sphere is shown in figure 7. The first two waves of ions are visible in the ion current time dependence. The shape of the ion current pulse indicates the presence of several relatively short waves in the plasma. A few intense waves in the head of the plasma torch are followed by a low-speed plasma, without intense oscillations. This plasma is close to laminar (without significant turbulents). From figures 4–6, it follows that the main contribution to the signal of a slow plasma is made by the direction of 20–40 degrees.

3.2. *Copper cathode – molybdenum anode*

The ion current diagrams for the molybdenum anode are shown in figures 8–10. The qualitative difference between these diagrams and diagrams for an iron anode is the absence of a local minimum of the ion current on the axis of the ion source. There is also no obvious second wave front at the periphery of the plasma torch. The first ion front propagates at approximately the same speed of 4×10^6 cm·s^{-1} for 5 kA and 4.7×10^6 cm·s^{-1} for $U = 10$ kV.

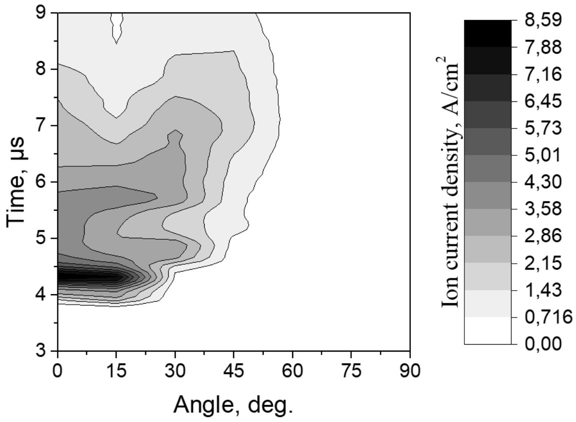

Figure 8. Time and spatial distribution of ion current for $U = 5$ kV. Mo anode.

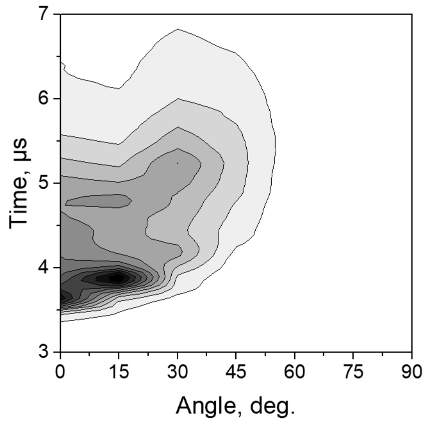

Figure 9. Time and spatial distribution of ion current for $U = 8$ kV. Mo anode.

The dependences of the total ion current integrated over the surface of the hemisphere are shown in figure 11. On the presented dependences, several ion current waves passing through a hemisphere with a radius of 15 cm are also visible. The duration of the signal of the laminar part of the plasma flow is somewhat longer than in the case of the iron cathode.

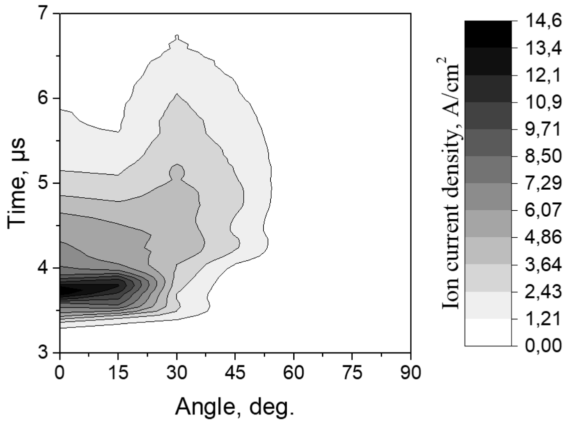

Figure 10. Time and spatial distribution of ion current for $U = 10$ kV. Mo anode.

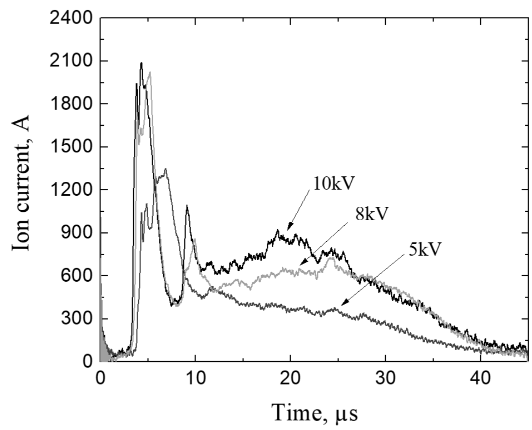

Figure 11. Calculated total ion current at hemisphere with 15 cm radius.

3.3. *Total ion erosion*

The method used in this research does not allow obtaining the mass-charge and energy composition of the flow. In addition, this composition is more strongly dependent on time and direction. Therefore, an accurate analysis of total ionic erosion is impossible. Figure 12 presents an estimate of total ion erosion under the assumption that the ion flux is a stream of double charged copper ions. The obtained data on specific ionic erosion substantially exceed those obtained earlier for average discharge currents [8]. However, it should be noted that these data cannot be directly compared with the values of ionic erosion for the cases, when a stable discharge was used for which the mass and charge composition of the ion flow is well known.

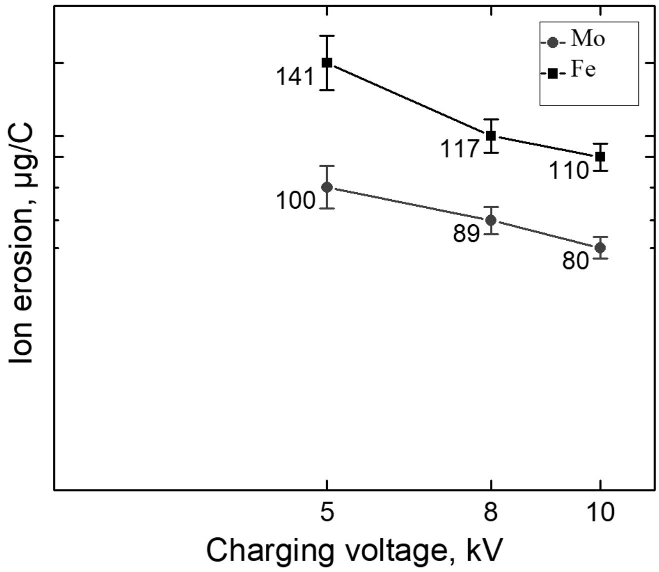

Figure 12. The dependence of ion erosion on the charging voltage.

The dependence in figure 12 is not very pronounced, but allows us to conclude that the efficiency of plasma formation decreases slightly with the increase of current. Ion erosion in case of the refractory Mo anode is somewhat smaller. This may indicate that the anode can make a significant contribution to plasma generation.

An important feature of the ion flow is its good repeatability from pulse to pulse (1% standard deviation), and from series to series (5% standard deviation). The total mass erosion of parts of the ion source (anode, cathode and insulator) is significantly higher than ion erosion. In contrary to the ion erosion, the values of total erosion differ significantly for different series of experiments under the same conditions. The erosion of the overall source design is in the range from 350 to 650 $\mu g \cdot C^{-1}$ for $U = 5$ kV and from 850 to 2000 $\mu g \cdot C^{-1}$ for $U = 10$ kV. The total mass erosion is substantially lower when we used the molybdenum anode in comparison with the iron one.

4. Discussion

The obtained results allow us to state that the designed plasma source is an effective ion source, since specific ion erosion is significantly higher than that for arc sources with currents up to 1 kA [8]. However, it should be taken into account that the parameters of the plasma torch obtained substantially change with time. If the first plasma front represents the front of high-speed ions with a relatively low concentration, then the laminar tail of a low-speed plasma has a significantly greater concentration. This is confirmed by the fact that at high voltages at the ion detector (< -60 V) during the propagation of the ion current tail, discharges between the detector and the analyzer wall occurred. Such discharges can only be caused by an increase in the concentration of charge carriers in the analyzer housing. Distribution of macroparticles and neutral vapor near the exit of the plasma source is still unexplored. Macroparticles have dimensions of up to hundreds of microns and can significantly affect the “point z-pinch” formation process. However, macroparticles having low speeds will not be able to fly far away from the source output by the time the pinch driving pulse is applied. The ion flow composition of the plasma torch various parts at different points in time has remained unexplored and additional spectrometric studies of the plasma flow would be useful.

5. Conclusion

The plasma ion flow formed by the microsecond vacuum arc plasma gun at peak current up to 11 kA has been investigated. The copper cathode and iron or molybdenum anodes with polyethylene insulator were used. The plasma gun was powered by pulse generator with charging voltage up to 10 kV. Features of the plasma ion flow were measured using small-sized ion collector analyzers. Spatial distribution of the ion flow and the total ion erosion of the plasma gun were determined. The measurement results show that the plasma torch had an expansion angle up to 45° from the axis. The ion velocity estimations yield values of $(3–5)\times10^6$ cm·s^{-1}, that is slighty higher in comparison with typical vacuum arc ion velocity. The total electrode erosion was measured by weighing after a few dozen shots. The ion flow had good repeatability from pulse to pulse, and from series to series. In contrary, the values of total erosion differ significantly for different series of experiments under the same conditions. The ion erosion was measured to be significantly higher than that for arc sources with currents up to 1 kA.

Acknowledgements

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References

[1] Brown I G 2004 *The Physics and technology of ion sources* (Weinheim: Wiley-VCH) 396 p
[2] Tanaka K, Han L, Zhou X and Anders A 2015 *Plasma Sources Science and Technology* **24** 045010
[3] Korenev S A, Puzynin I V, Samoilov V N and Sissakian A N 1997 *Proc. of the 2nd Inter. Conf. on Accelerator-Driven Transmutation Technologies and Applications (Kalmar, Sweden)* vol. 2 (Uppsala University) pp 1061–1064
[4] Russkikh A G, Shishlov A V, Zhigalin A S, Oreshkin V I, Chaikovsky S A and Baksht R B 2011 *Plasma Sources Sci. Technol.* **20** 035011
[5] Rousskikh A G, Artyomov A P, Zhigalin A S, Fedunin A V, Oreshkin V I and Baksht R B 2017 *Proc. of the 21st International Conference on Pulsed Power (PPC) (IEEE)* pp 1–4
[6] Yushkov G Y, Nikolaev A G, Frolova V P, Oks E M, Rousskikh A G and Zhigalin A S 2017 *Physics of Plasmas* **24** 123501
[7] Rousskikh A G, Zhigalin A S, Oreshkin V I, Chaikovsky S A, Labetskaya N A and Baksht R B *Physics of Plasmas* **18** 092707
[8] Boxman R L, Martin P J and Sanders D M (eds.) 1995 *Handbook of vacuum arc: Science and technology* (Park Ridge, New Jersey, USA: Noyes Publications) 772 p